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FORECASTING PRECIPITATION ON THE WEST SLOPE OF COLORADO

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ABSTRACT

The problem of forecasting precipitation on the west slope of Colorado is discussed. Synoptic situations which result in precipitation on the west slope of Colorado are described. These lead to the selection of five map types upon which an objective aid for forecasting is based. A number of variables are explored under each type and are combined by graphical correlation techniques to arrive at final forecasting charts. The results and test are summarized in the form of skill scores above chance and percent correct forecasts.

CONTENTS

INTRODUCTION

The purpose of this study is to set up objective procedures for forecasting rainfall in western Colorado. In developing the procedures, considerable time was spent in exploratory efforts to find relations between the factual information available at forecast time, and subsequent weather. The methods of attack follow in general those used in similar studies by Brier [1], Vernon [2], Penn [3], and others. The principal sources of ideas for the selection of variables to be tested and for typing situations were the forecasting staff at the Denver Forecast Center and previous research papers, including those by Reed [4], Carpenter [5], and Laird [6].

The forecast area covered in this study includes all of the stations from the north to south borders of Colorado west of the Continental Divide for which sufficient records were available from the surface and other charts. Reporting stations selected from this area were Craig, Eagle, Grand Junction, and Durango. Craig is in northwestern Colorado, Grand Junction and Eagle are in the west central, and Durango is located in the southwestern part of the state. A study of the terrain shows that the exposures of the four stations are quite dissimilar; Durango at an elevation of 6,800 feet has a southern exposure, Grand Junction at 4,800 feet and Craig at 6,300 feet are situated with their lowest terrain to the west-northwest, while Eagle at 6,500 feet is a typical mountain station. The variation in altitude of 2,000 feet is not too great, for some of the mountain passes in the forecast area go to nearly 12,000 feet.

For purposes of verification some definite distinction between a precipitation day and a no-precipitation day was necessary. Because so many areas on the west slope are higher than the reporting stations and are therefore likely to get more precipitation than the stations themselves, it was decided that a trace at any one station should define a precipitation day.

The spring months only, March, April, and May, were used in this investigation for two reasons. First, the synoptic conditions are more or less similar during this period of rapidly moving systems, and are quite dissimilar to the summer or mid-winter conditions. Second, the spring months produce more weather than the other seasons as well as more frequent and rapid changes in weather.

Data from the springs of 1947 and 1948 were used to develop the original graphs and data from the spring of 1949 were used as independent or test data. The time for all surface data is 2330 MST and for all upper air data 2030 MST. The forecast period is the twelve hours from 0530 MST to 1730 MST of the following day.

PRECIPITATION TYPES

As a background for much of the discussion to follow, a brief description is now given of the important synoptic types that produce precipitation on the west slope of Colorado. As has been pointed out by forecasters of the Rocky Mountain Region, west slope and east slope weather problems are different, chiefly in that a marked change in the wind to bring about upslope flow is nearly always necessary for significant precipitation to occur along the east slope, while on the west side of the mountains, the normal flow of the air is upslope. In an earlier paper, the writer [6] studied weather charts from 1943 through 1947 for all of the twelve months, and from a detailed analysis of poor weather conditions (fair weather types were passed over rather briefly), found that the following four fairly specific synoptic types produce most of the precipitation on the west slope:

1. The Pacific front, southerly type, usually moves into Colorado through Southern California and Arizona. It may or may not produce general precipitation to the west of Colorado. It is accompanied by a surface low pressure system and, in general, an upper trough. Cold air advection may be weak to strong; the relative humidity is nearly always high at upper levels. The rate of movement and consequently the duration of the storm is closely related to whether there is an open trough or a closed Low aloft. This type almost always produces precipitation over western Colorado, and the problem becomes one of timing.

2. The Pacific front, northerly type, moves inland across the northern or middle Pacific coast to Idaho, Nevada, and Utah. The characteristics of this type are similar to those of the southerly type, except that the changes are farther north, and western Colorado may receive only the weak southern tip of this front. The direction of wind flow aloft may change only 20° to 40° in the upper trough with one of these fronts, and therefore moisture content becomes a critical factor as to whether the west slope valleys will receive even a trace of precipitation. The two Pacific types were combined in the present study because of the wide range of areas affected by each one and because of similar characteristics.

3. The upper level anticyclone centered over the lower Mississippi Valley is associated with some of the heaviest downpours, together with numerous thunderstorms, throughout the mountain and intermountain region. To receive the greatest amount of rainfall western Colorado should be in southerly or southwesterly wind flow along the back side of the high cell. This normally is a late summer or fall occurrence and therefore does not apply as a definite type in this study.

4. The continental polar front which moves southward out of Canada may or may not produce precipitation on the west slope depending upon several factors. Many of these fronts move down along the east slope of the mountains and out eastward producing no precipitation at all west of the Continental Divide. If the top of the cold air is at least 10,000 feet above sea level, and particularly when a surface low center or deep trough has developed over or near Nevada, all of the western valleys may get moderate rain or snow.

PRELIMINARY STUDY

Since in this study all of the maps had to be considered instead of just the rain type, some variable which could be evaluated regardless of frontal systems had to be used as a starting point. It was found that the most predominant feature of a rain type was the low pressure system over the Plateau, while the most prominent feature of the dry type was the high pressure over the same area. Therefore the difference in sea level pressure between San Francisco and Milford, Utah was one of the first variables investigated. This algebraic difference gives a good indication of a High or Low over the Plateau approaching Colorado but not yet upon it.

Because previous studies, such as those mentioned in the introduction, and the experiences of the Denver staff had suggested that moisture in the upper levels is also a critical element, a preliminary analysis was made of the radiosonde observations from Boise, Ely, Medford, Phoenix, Las Vegas, and Lander. This analysis showed the moisture at Ely to have the highest correlation with precipitation in western Colorado during the forecast period, if no other factors were considered.

A preliminary study was then completed using all of the maps for March, April, and May 1947 and 1948. With the two variables, (1) relative humidity at 700 mb. at Ely, and (2) sea level pressure difference, San Francisco minus Milford, a scatter diagram was plotted and the "dry" side of the graph separated from the "wet" side with a curved line. From this separation an accuracy of about three out of four was obtained. On check data the accuracy was a little less. A study of the failures in this procedure showed, as was expected, that a good many other factors should be considered. After these failures were analyzed, a typing procedure together with additional variables which became apparent, was decided upon as the best approach.

MAP TYPES AND VARIABLES

Four definite map types related to the precipitation types already discussed and a fifth so-called "indefinite" type were set up. These classifications were: (1) The

700-mb. Low type, (2) the MP front type, (3) the CP front type, (4) the MP and CP double front type, and (5) the indefinite type. These types are defined and described in detail below. The 700-mb. Low type needs some explanation since it often accompanies one of the frontal types. After the front passes to the east or south of the forecast area, the variables used for frontal types can no longer be used. Also whether or not precipitation continues over western Colorado during the following forecast period depends a great deal on whether or not an upper Low has developed and its position with respect to the Continental Divide.

The following variables were investigated for these five types; considerable time and effort went into testing their usefulness, and those which proved to be significant were included in the final procedures:

1. Sea level pressure difference, San Francisco minus Milford. (Used for types 1, 2, 3, and 5.)
2. 700-mb. relative humidity at Grand Junction. (Used for type 2.)
3. Average 700-mb. relative humidity upstream. (Used for types 2, 3, and 4.)
4. Position of the 700-mb. low center. (Used for type 1.)
5. Average mixing ratio at Grand Junction, surface to 700 mb. (Not used.)
6. 700-mb. wind direction at Grand Junction. (Used for type 5.)
7. 700-mb. relative humidity at Ely. (Used for for type 5.)
8. Surface dew points at the verification stations. (Not used.)
9. Surface dew point spread at the verification stations. (Not used.)
10. Milford sea level pressure. (Not used.)
11. Sea level pressure difference, Billings minus Grand Junction. (Used for type 4.)

INVESTIGATIONS BY TYPE

TYPE 1. 700-MB. LOW

Type 1 included all cases where the 700-mb. chart showed the center of a closed Low to be over Colorado, Utah, Arizona, New Mexico, or those portions of Nevada and California east of a line connecting the northwest corner of Utah and Point Conception on the California coast. (See fig. 1.)

A forecast of precipitation on the basis of the existence of such a Low alone would yield a high forecast accuracy. There were 18 Lows in this area during the 6 months of dependent data, 15 of which produced precipitation at at least one of the four verification stations. Further study of the position of the center of the Low with respect to the Continental Divide, in conjunction with the indications of the sea level pressure difference between San Francisco and Milford gave even better results. If the center of the Low is east of the Divide and the sea level pressure difference is negative, indicating high pressure building up or approaching western Colorado, the likelihood of precipitation is less than if the low center is west of the Divide. These results are given in table 1. These results are tentative and must remain so until enough additional cases of the same type have been accumulated to verify them. Although there were eleven Lows in the three test months of 1949, and all produced precipitation, all were west of the Divide.

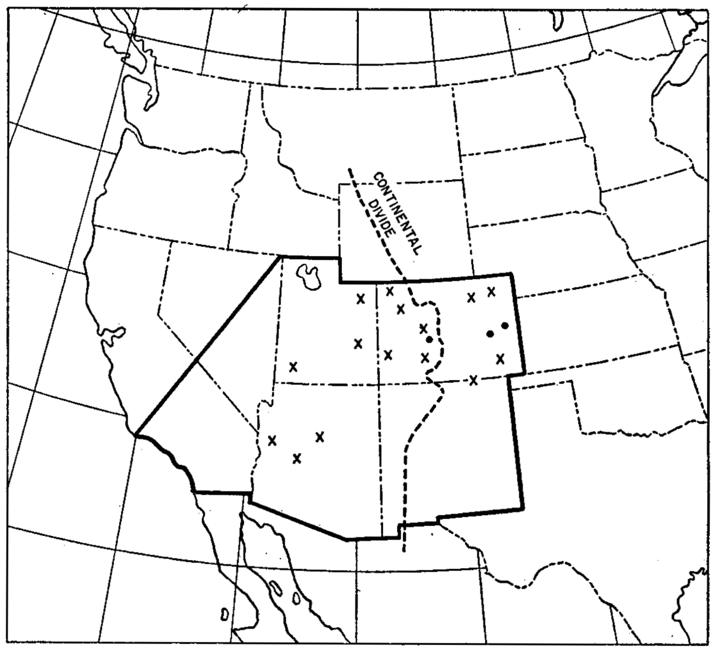

Figure 1.—Map showing area (heavy outline) in which center of Low at 700 mb. must be located for case to be classified as Type 1. Cross indicates location of Low in cases followed by precipitation during forecast period, and dot, no-precipitation.

Table 1.—*Ratio of number of precipitation cases (numerator) to total number of cases (denominator) for joint categories of sea level pressure difference between San Francisco (SFO) and Milford (MLF), and of the position of the 700-mb. Low relative to the Continental Divide.*

Type 1. 700-mb. Low		Position of the 700-mb. Low relative to the Continental Divide	
		West	East
Sea Level Pressure Difference, SFO−MLF	>0	$\frac{10}{11}$	$\frac{3}{3}$
	<0	$\frac{1}{1}$	$\frac{1}{3}$

TYPE 2. MP FRONTS

Type 2 included all maps with a Pacific front within the continental United States and west of Colorado on the 2330 MST map. A little difficulty was encountered on a very few maps because once in a while a very weak front was carried on the map when characteristics were so weak as to be negligible. Also there were a few instances where fronts carried at 2330 MST were dropped at the

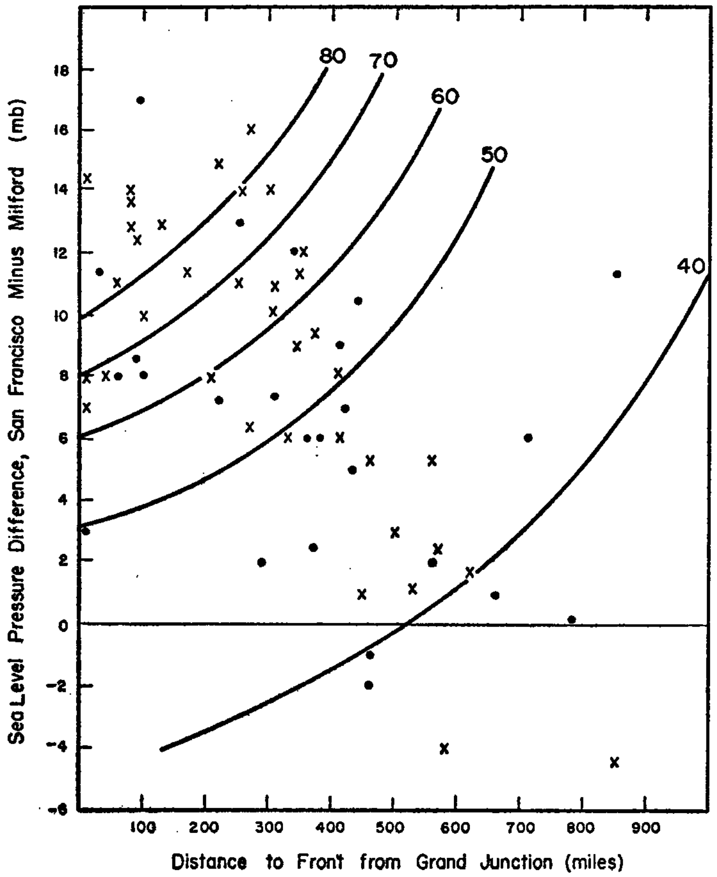

FIGURE 2.—Scattergram of precipitation (x) and no-precipitation (•) cases for Type 2 maps. Isopleths are drawn for percent frequency ("probability") or precipitation occurrence.

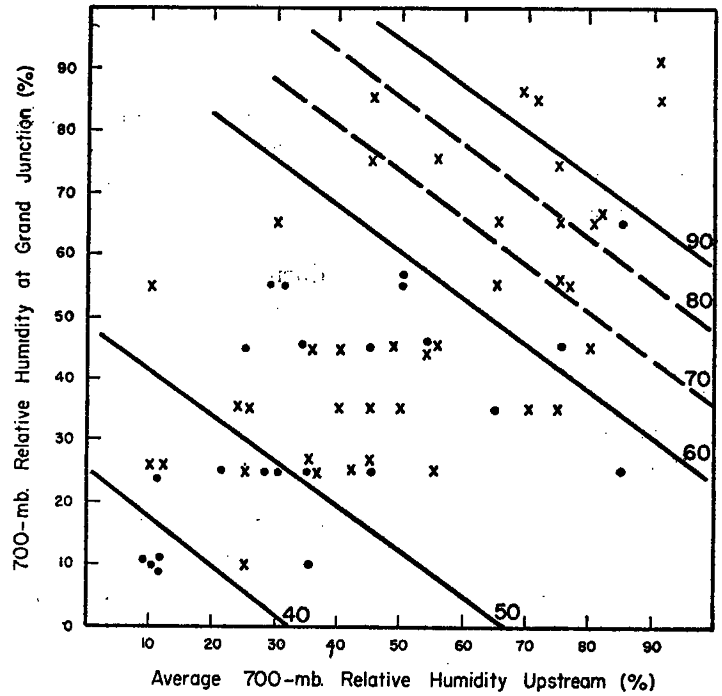

FIGURE 3.—Scattergram of precipitation (x) and no-precipitation (•) cases for Type 2 maps. Isopleths are drawn for percent frequency ("probability") of precipitation occurrence.

following period. However, to have a specific criterion for defining type 2 it was decided to retain the original definition which was fulfilled by any MP front at 2330 MST.

The following are the final variables selected for this type: (1) Sea level pressure difference, San Francisco minus Milford, (2) distance, in miles, to the front from Grand Junction, (3) 700-mb. relative humidity at Grand Junction, and (4) average 700-mb. relative humidity upstream from western Colorado. The upstream relative humidity was found as follows: Two contour lines were drawn upstream from the northwest and southwest corners of Colorado parallel to the contour lines of the 700-mb. chart. If the average wind velocity was less than thirty knots the inner circle of raobs within the contour channel was considered, including Ogden, Ely, Las Vegas, Phoenix, and Albuquerque. If the speed was greater than thirty knots, Boise, Oakland, and Santa Maria were also considered.

The variables were combined by graphical correlation techniques which have been adequately explained in a number of recent papers [1, 2, 3] and need not be described in detail here. The variables were combined according to the following diagram:

Sea level pressure difference, San Francisco minus Milford; Distance to front from Grand Junction	Probability from figure 2	Forecast from figure 4
700-mb. relative humidity at Grand Junction; Average 700-mb. relative humidity upstream	Probability from figure 3	

Only a "forecasting" line, or line of best separation of precipitation from no-precipitation, is drawn in figure 4. A forecast of precipitation is made if the point falls above the line and no-precipitation if the point falls below the line.

TYPE 3. CP FRONTS

Type 3 included all maps with a continental front moving southward through Montana or Wyoming. Stationary fronts were not included in this category.

The variables selected for this type are: (1) Sea level pressure difference, San Francisco minus Milford, and (2) average 700-mb. relative humidity upstream. The variables were combined in a scatter diagram, figure 5. That the line of separation on this chart is almost horizontal indicates that the pressure difference is adding but little to the results obtainable from the relative humidity alone. Moreover, none of the other variables investigated under this type added materially to the results obtained from the average relative humidity upstream.

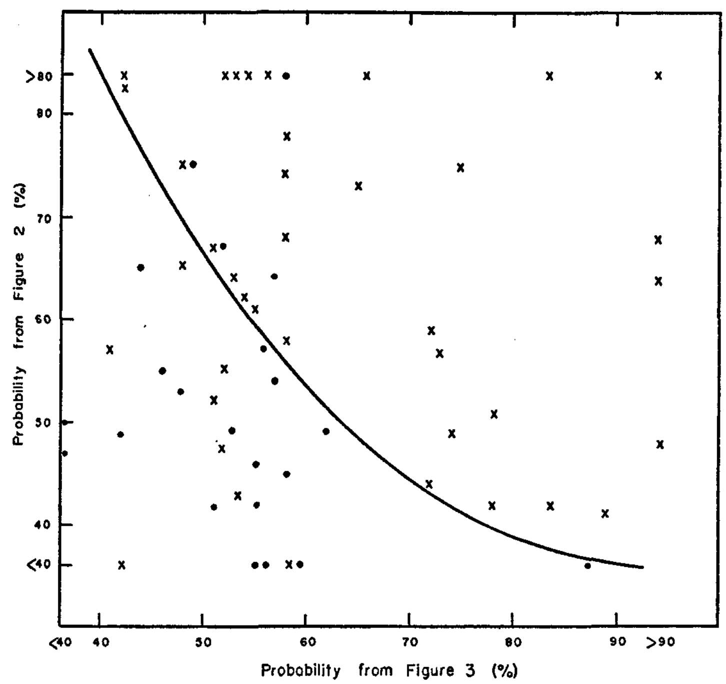

FIGURE 4.—Scattergram of precipitation (x) and no-precipitation (•) cases for Type 2 maps plotted as a function of probabilities from figures 2 and 3. Forecast "precipitation" for points above line of separation, "no-precipitation" for points below.

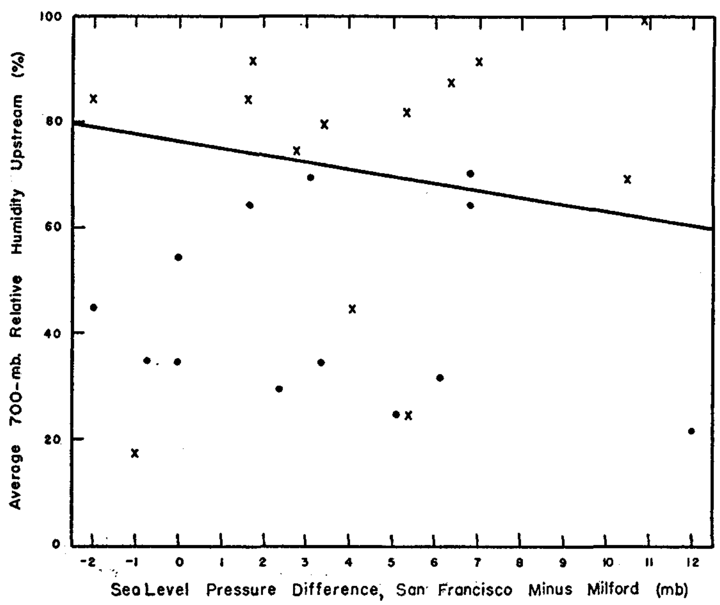

FIGURE 5.—Scattergram of precipitation (x) and no-precipitation (•) cases for Type 3 maps. Forecast "precipitation" for points above line of separation, "no-precipitation" for points below.

TYPE 4. MP PLUS CP FRONTS

Type 4 included all maps on which both MP and CP types of fronts as described under types 2 and 3 exist at the same time. Stationary fronts which stagnate along the east slope of the mountains of Colorado and Wyoming are not included here.

The variables selected in this type are: (1) Sea level pressure difference, Billings minus Grand Junction, and

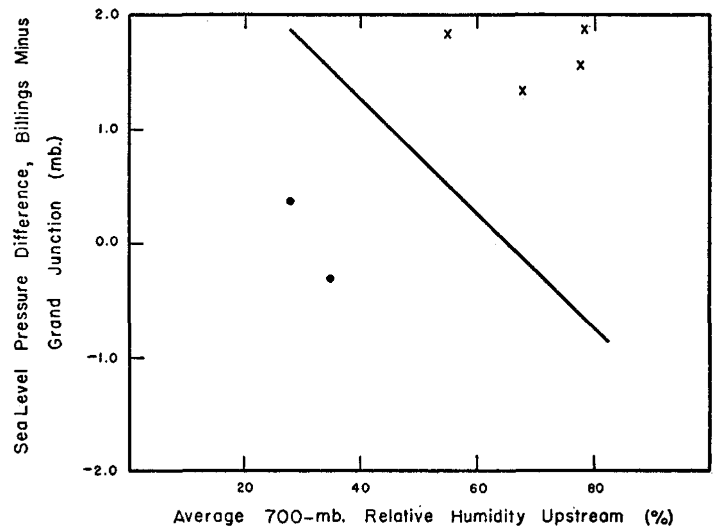

FIGURE 6.—Scattergram of precipitation (x) and no-precipitation (•) cases for Type 4 maps. Forecast "precipitation" for points above line of separation, "no-precipitation" for points below.

(2) average 700-mb. relative humidity upstream. The scatter diagram combining these two variables is shown in figure 6. While a very good separation of the cases is evident, the few cases of this type makes the position of the line of separation rather indefinite. Until more cases are included only an approximation of the best position of the line is possible.

TYPE 5. INDEFINITE

Type 5 included all maps not belonging to one of the other types. This "indefinite" type was the most frequent single type and was the most difficult to handle. The dry type or Plateau High usually fell into this classification. The indifferent type or so-called flat pressure map often was placed in this category. No definite fronts were present, but often considerable upper level moisture and a westerly wind flow brought into play the orographic effects.

The final variables selected under this type were: (1) Sea level pressure difference, San Francisco minus Milford, (2) 700-mb. relative humidity at Ely, and (3) the 10,000-foot, or 700-mb., wind direction at Grand Junction. These were combined as follows:

Sea level pressure difference, San Francisco minus Milford	Probability from figure 7	Forecast from figure 9
700-mb. relative humidity at Ely		
Sea level pressure difference, San Francisco minus Milford	Probability from figure 8	
700-mb. wind direction at Grand Junction		

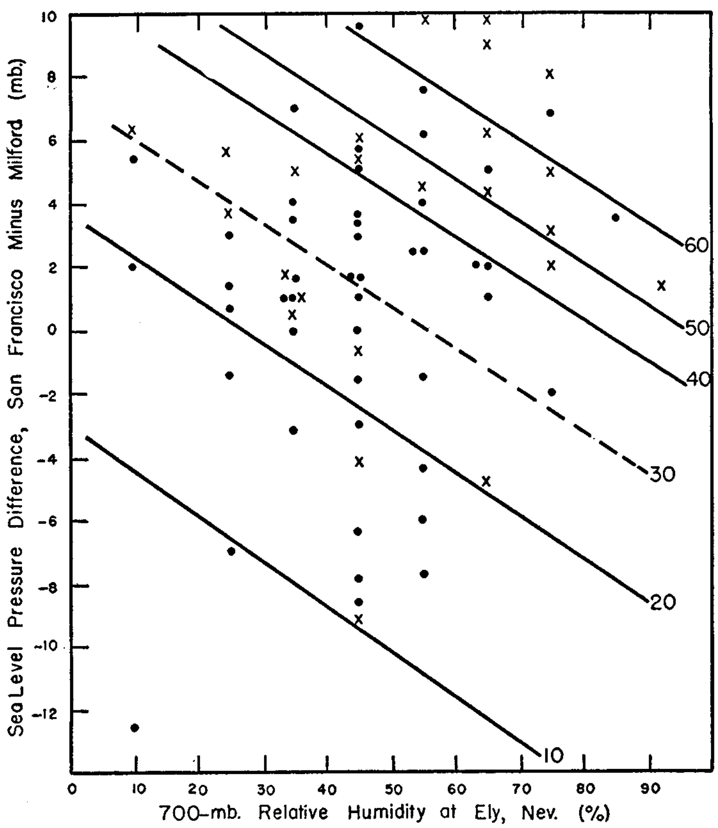

FIGURE 7.—Scattergram of precipitation (x) and no-precipitation (•) cases for Type 5 maps. Isopleths are drawn for percent frequency ("probability") of precipitation occurrence.

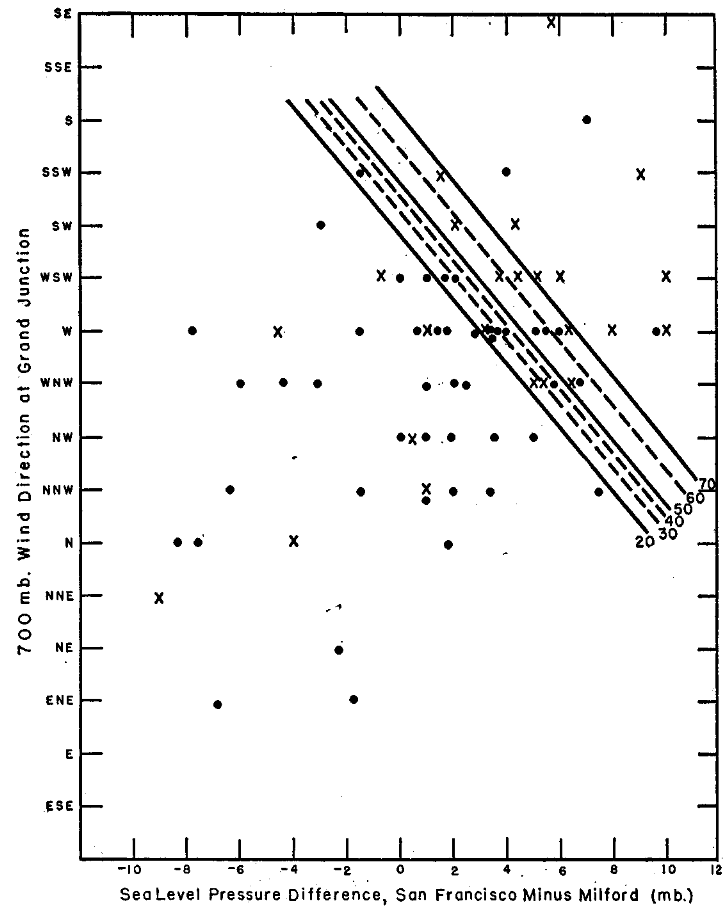

FIGURE 8.—Scattergram of precipitation (x) and no-precipitation (•) cases for Type 5 maps. Isopleths are drawn for percent frequency ("probability") of precipitation occurrence.

A line of separation was drawn on this chart, with rain cases predominately above the line and non-rain cases below the line.

RESULTS

A total of 275 maps were analyzed, including both original and test data. The results are summarized by types in table 2.

No attempt was made to compare these results directly with official Weather Bureau forecasts since a strict verification of the official forecasts is virtually impossible. That is, a forecast of showers over the higher mountains, southwestern, or northwestern mountains is often correct even though none falls at any of the valley stations, and district forecasts for the specific stations are not made.

CONCLUSIONS

The results point out several facts of importance. First, the 700-mb. Low type produced a high skill score and percentage correct, and the indefinite type gave in general the least satisfactory results. This was to be expected since the first type is obviously a precipitation type while the last type includes all maps not of definite characteristics. However, it means that more refinement should be attempted in this last type, particularly since it is the most frequent category.

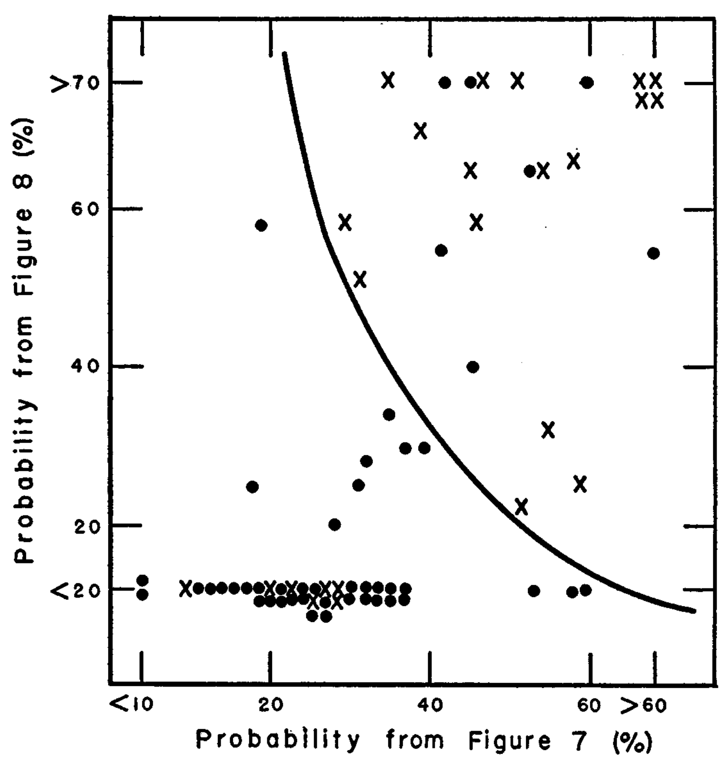

FIGURE 9.—Scattergram of precipitation (x) and no-precipitation (•) cases for Type 5 maps plotted as a function of probabilities from figures 7 and 8. Forecast "precipitation" for points above line of separation, "no-precipitation" for points below.

TABLE 2.—*Summary of skill scores and percent correct for each type for original and test data*

Type	Cases	Skill Score*	Percent correct
Original Data, 1947–48			
1. 700-mb. Low	18	0.60	89
2. MP front	62	.63	82
3. CP front	26	.62	81
4. MP plus CP front	6	1.00	100
5. Indefinite (all others)	72	.56	81
Total	184	.65	83
Test Data, 1949			
1. 700-mb. Low	11	(1)	100
2. MP front	40	0.21	63
3. CP front	7	.33	71
4. MP plus CP front	none		
5. Indefinite (all others)	33	.29	64
Total	91	.36	67

1 Indeterminate

* *Skill scores were computed from the formula:*

$$\text{Skill Score}=\frac{C-E_c}{T-E_c}$$

Where: C=observed number of correct forecasts.
T=total number of forecasts.
E_c=expected number of correct forecasts due to chance, computed from the marginal totals of the contingency table.

Second, in the interest of keeping the study in a simple form, several important meteorological elements were omitted. Some of these are: (1) 3-, 6-, and 12-hour pressure changes, (2) stability of the air, (3) deepening and filling of pressure systems, (4) subsidence, (5) convergence, and (6) cold and warm air advection. Since all of these should be considered in making a forecast, this study should be considered an aid and not a complete method.

Third, the forecast period is for 12 hours; further efforts will be necessary to expand this period to a second 12 hours. In doing so the use of some of the same variables may be satisfactory, but it is obvious that their values will not be the same. By the second 12-hour period the conditions which produced precipitation often have passed and the precipitation ended. Therefore, to expand the forecast period another 12 hours becomes almost an entirely new problem.

Fourth, exploratory efforts in other seasons of the year showed clearly that different seasons must be treated differently in this type of approach. Tests on the three winter months gave unsatisfactory results.

Fifth, three years of records are inadequate for conclusive results and further testing will be necessary. Particularly those types which occur rather infrequently will need further refinement with the addition of more data.

ACKNOWLEDGMENTS

The suggestions of Mr. Woodrow Dickey and Mr. Forrest E. Horning were extremely valuable in solving various problems as they arose and their help is greatly appreciated. Acknowledgments are made also to all of the other members of the Denver forecast staff for their helpful suggestions and criticisms. The statistical and graphical procedures were under the direction of Mr. Dickey.

REFERENCES

1. G. W. Brier, *Predicting the Occurrence of Winter Time Precipitation for Washington, D. C.*, U. S. Weather Bureau, Washington, 1945.
2. E. M. Vernon, "An Objective Method of Forecasting Precipitation 24–48 Hours in Advance at San Francisco, California", *Monthly Weather Review*, vol. 75, No. 11, November 1947, pp. 211–219.
3. Samuel Penn, "An Objective Method for Forecasting Precipitation Amounts from Winter Coastal Storms for Boston", *Monthly Weather Review*, vol. 76, No. 8, August 1948, pp. 149–161.
4. T. R. Reed, "The North American High-Level Anticyclone", *Monthly Weather Review*, vol. 61, No. 11, November 1933, pp. 321–325.
5. A. B. Carpenter, The Use of the 700-Millibar Data in Precipitation Forecasting for Utah, U. S. Weather Bureau Airport Station, Salt Lake City, Utah, 1947 (unpublished manuscript on file in Weather Bureau Library, Washington, D. C.).
6. H. B. Laird, Flying Weather of Western Colorado, Weather Bureau Airport Station, Denver, 1948 (unpublished).